

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Research Laboratory (AFMC) AFRL/PRS 5 Pollux Drive Edwards AFB CA 93524-7048				10. SPONSOR/MONITOR'S ACRONYM(S)	
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

7. Separate items enclosed

P91
6111

10110011

MEMORANDUM FOR PRS (In-House Publication)

FROM: PROI (STINFO)

18 June 2002

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-VG-2002-152**
Greg Spanjers (PRSS) et al., "Herriott Cell Augmentation of a Quadrature Heterodyne Interferometer"
(viewgraphs only)

AIAA JPC

(Statement A)

(Indianapolis, IN, 07-10 July 2002) (Deadline = 30 June 2002)

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.

Comments: _____

Signature _____ Date _____

2. This request has been reviewed by the Public Affairs Office for: a.) appropriateness for public release and/or b) possible higher headquarters review.

Comments: _____

Signature _____ Date _____

3. This request has been reviewed by the STINFO for: a.) changes if approved as amended, b) appropriateness of references, if applicable; and c.) format and completion of meeting clearance form if required

Comments: _____

Signature _____ Date _____

4. This request has been reviewed by PR for: a.) technical accuracy, b.) appropriateness for audience, c.) appropriateness of distribution statement, d.) technical sensitivity and economic sensitivity, e.) military/national critical technology, and f.) data rights and patentability

Comments: _____

APPROVED/APPROVED AS AMENDED/DISAPPROVED

PHILIP A. KESSEL

Date

Technical Advisor

Space and Missile Propulsion Division

20021119 160



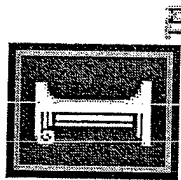
Herriott Cell Augmentation of a Quadrature Heterodyne Interferometer

Erik L. Antonsen
Rodney L. Burton
University of Illinois
Urbana-Champaign, IL

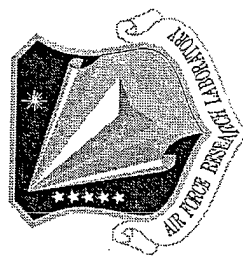
Greg G. Spanjers
Scott F. Engelman
AFRL Propulsion Directorate
Edwards AFB, CA

2002 HTPD
July 8-11, Madison, WI

DISTRIBUTION STATEMENT A:
Approved for Public Release -
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Herriott Cell Concept

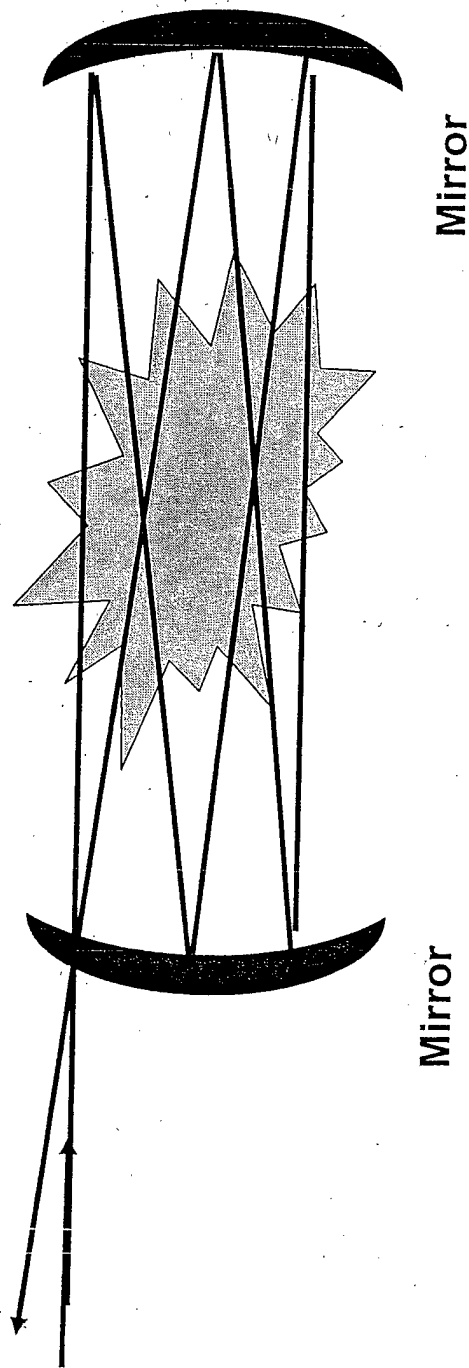


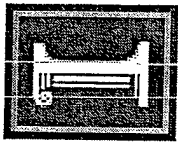
- Simple design requiring 2 concave mirrors and an off axis admission aperture
- Critical challenge is phase front maintenance for interferometry
 - Addressed:

- Confine large number of laser reflections to increase interferometric path lengths

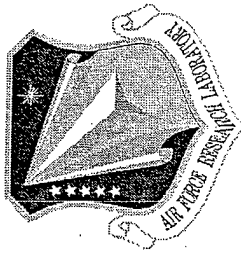
Antonsen, E. L., Burton, R. L., Engelman, S. F., Spanjers, G. G., "Herriott Cell Interferometer for Unsteady Density Measurements in Small Scale Length Thruster Plasmas," AIAA 2000-3431, 36th JPC, July 2000.

Plasma



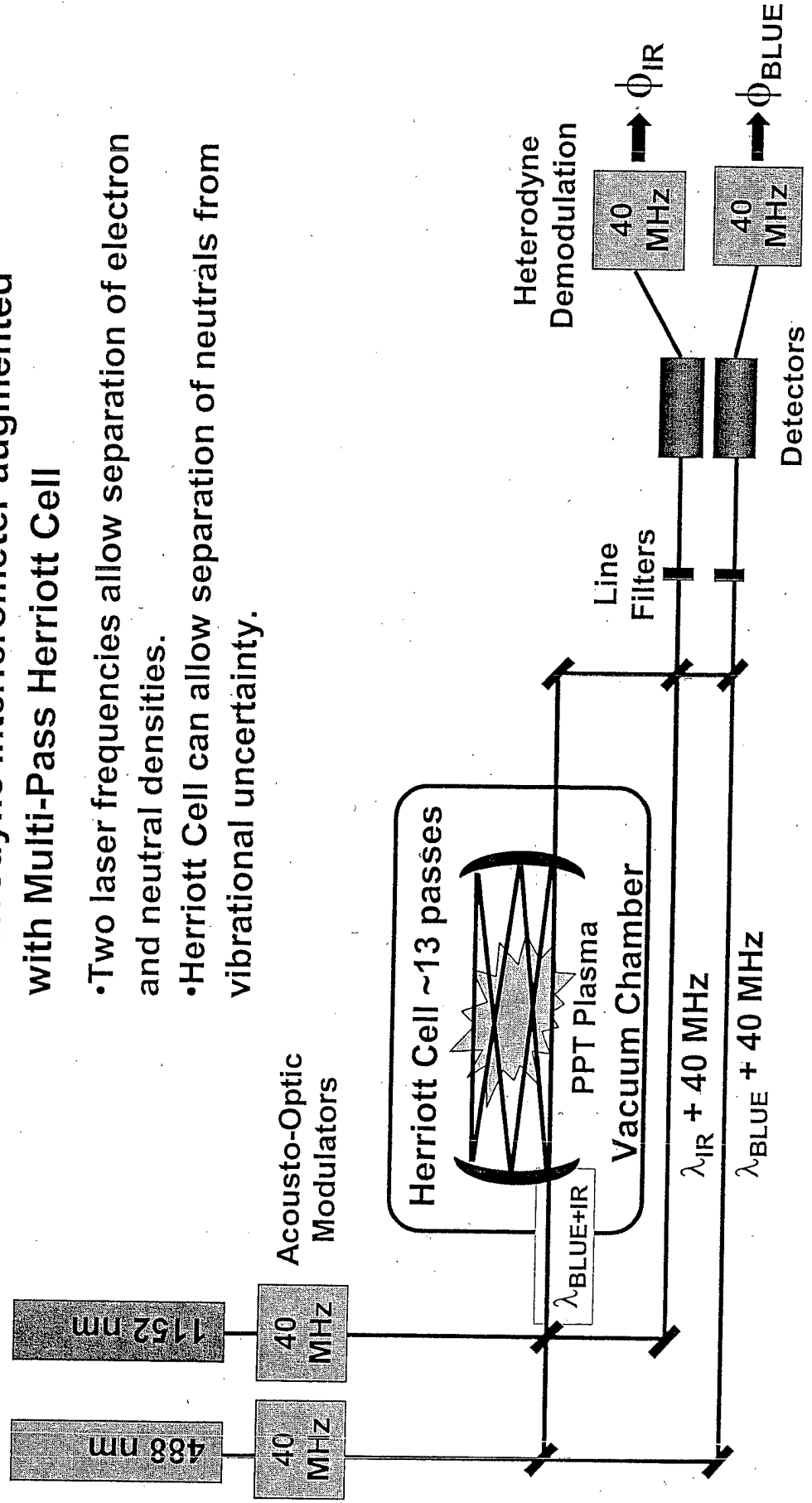


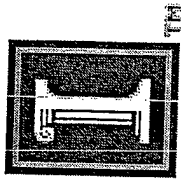
Herriott Cell Interferometer Diagnostic Layout



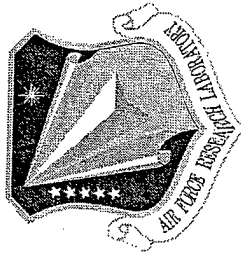
Heterodyne Interferometer augmented with Multi-Pass Herriott Cell

- Two laser frequencies allow separation of electron and neutral densities.
- Herriott Cell can allow separation of neutrals from vibrational uncertainty.





Multiple Reflections Increase Instrument Resolution



$$\Delta\Phi_{\text{TOTAL}} = \Delta\Phi_{\text{ELECTRONS}} + \Delta\Phi_{\text{NEUTRALS}} + \Delta\Phi_{\text{VIBRATIONS}}$$

For multiple shots averaged:

$$\Delta n = \sqrt{\Delta n_{\text{vibs}}^2 + \Delta n_{\text{PPT}}^2}$$

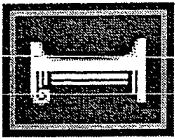
Total Density Uncertainty \rightarrow Δn \leftarrow Shot-to-Shot Thruster Variation \rightarrow Δn_{PPT}^2
 Δn_{vibs}^2 \leftarrow Vibrational Contribution (no dependence on N)

$$\Delta\Phi_{\text{ELECTRONS}} = C_e N \lambda \int n_e dl$$

$$\Delta\Phi_{\text{NEUTRALS}} = \frac{C_n N}{\lambda} \int n_n dl$$

$$\Delta\Phi_{\text{VIBRATIONS}} = \frac{C_v}{\lambda} \Delta L$$

High number of passes increase sensitivity to electron and neutral phase shifts without increasing vibrational noise

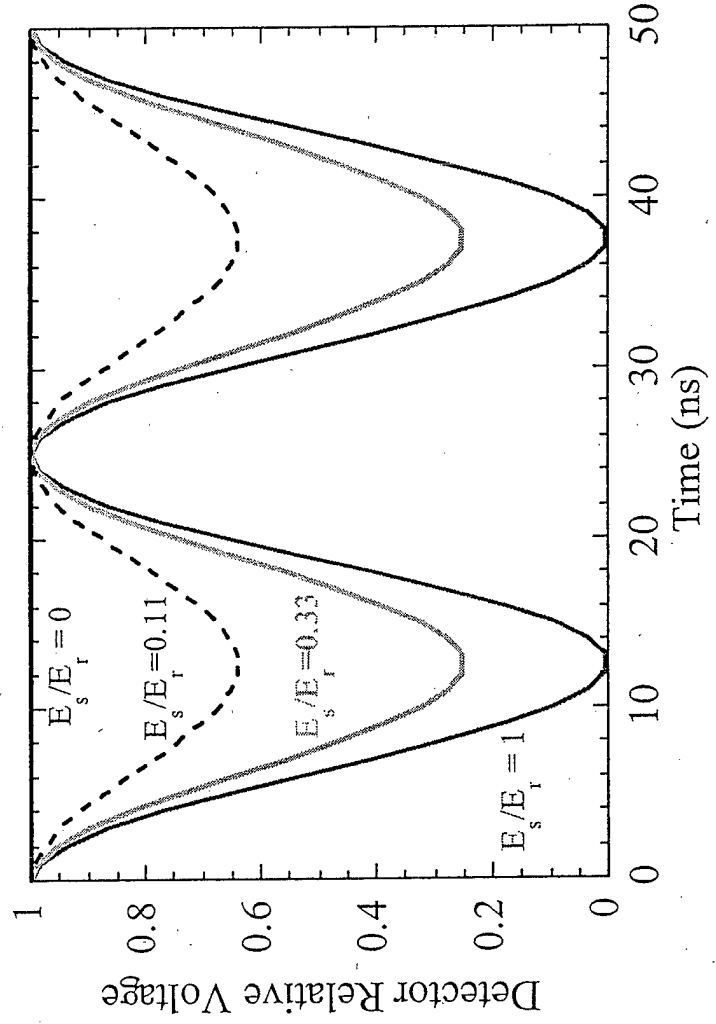


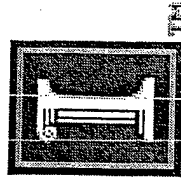
Unbalanced Beam Intensities

$$V\left(\frac{E_S}{E_R}\right) \propto E_R^2 \left[1 + \left(\frac{E_S}{E_R}\right)^2 + 2\left(\frac{E_S}{E_R}\right) \cos(\omega_A - \phi(t) - \gamma(x, y)) \right]$$

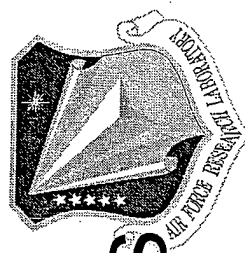
Effect of non-balanced intensities on the interferometer signal at the detector.

Relative intensities of the scene and reference beams are given above each trace.

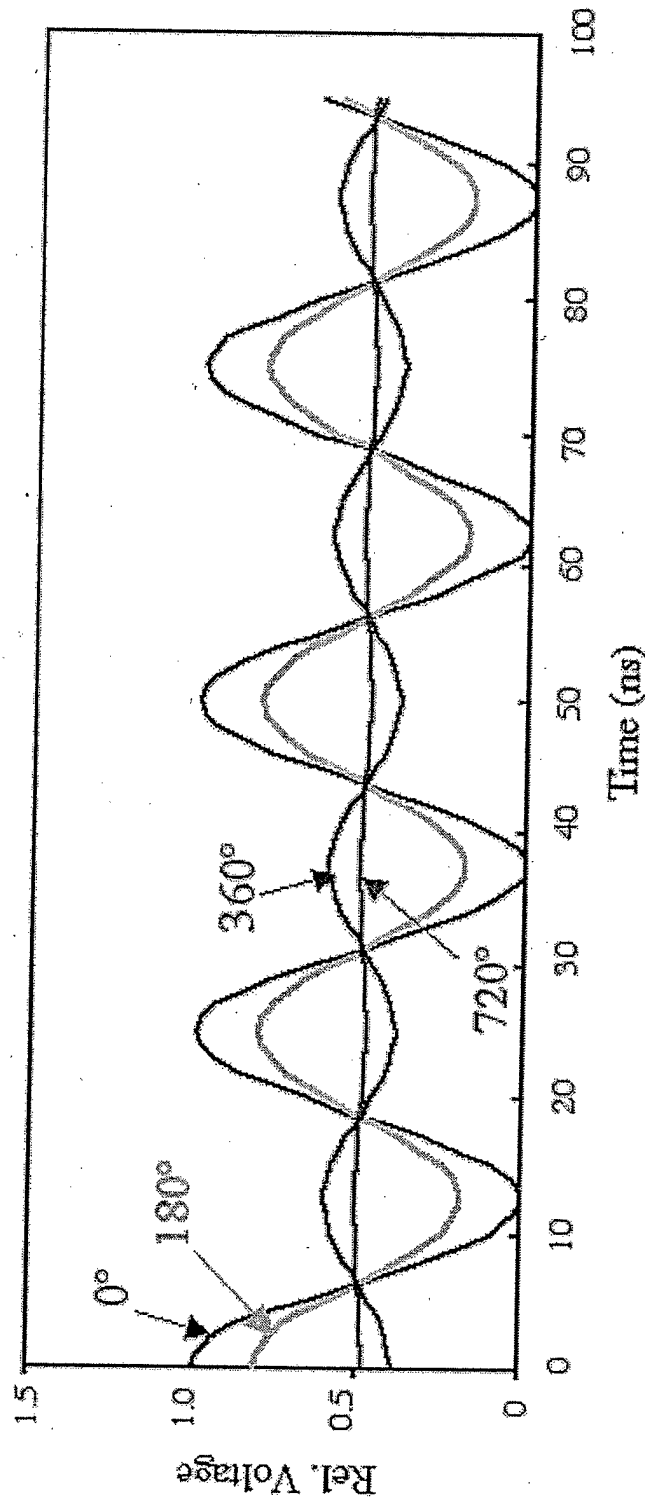


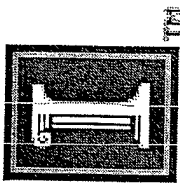


Phase Front Distortion Effects

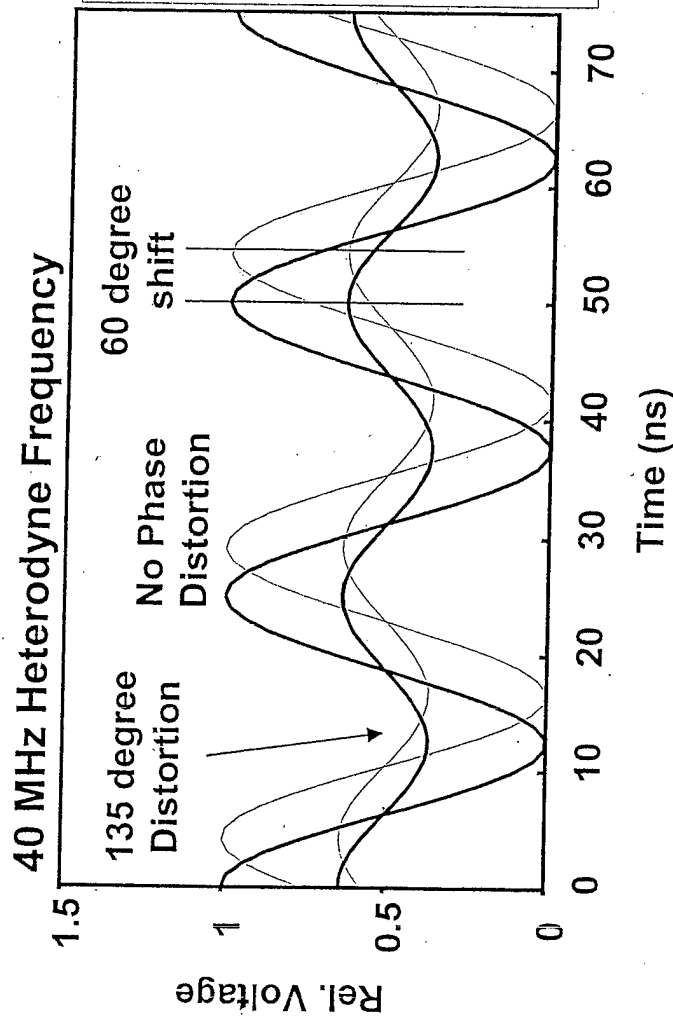
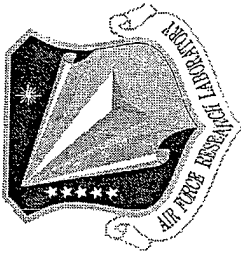


- The trace labeled "0" corresponds to zero phase distortion,
- "180" corresponds to $1/2$ wavelength distortion, etc.
- In each case, the distortion is presumed linear in one direction across the beam diameter and the beam is presumed square.



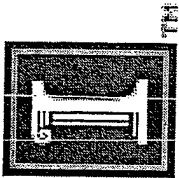


Fundamental Limit to Ultimate Resolution

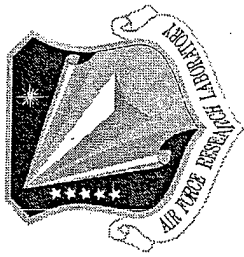


- Each Reflection degrades Phase Front of Scene Beam.
 - Distorted phase front will appear as a net phase shift compared to undistorted case
- With plasma, distorted phase front shifts same magnitude as undistorted case. Thus, density is correctly measured.

- Loss of Phase Front appears as a decreased S/N.
- Does not introduce systematic error to measurement

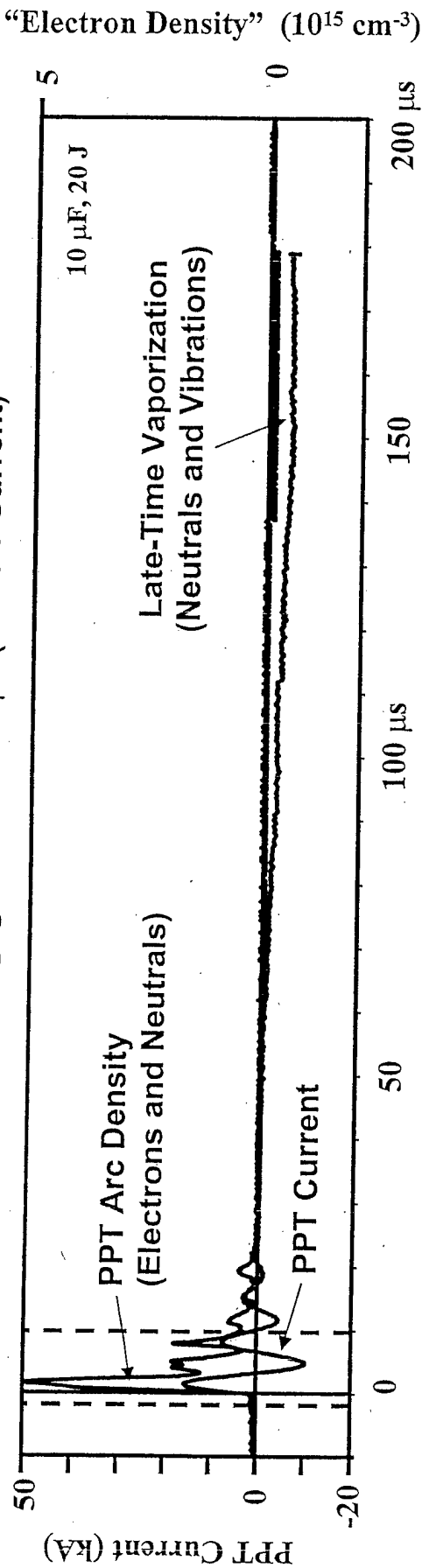


Data Reduction



$$\Delta\Phi = 2.8 \times 10^{-15} \lambda \int n_e dl - \frac{3.9 \times 10^{-29}}{\lambda} \int n_n dl - \frac{2\pi\Delta l}{\lambda}$$

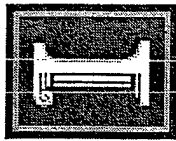
Assume: Vibrations Negligible for $\sim 50 \mu s$ during discharge ($f \sim 10$ kHz)
Electron Density Negligible after $\sim 50 \mu s$ (no PPT Current)



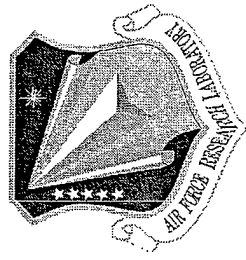
Vibrations Negligible
Only Electrons and
Neutrals Contribute

Electron Density Negligible
(no PPT Current)

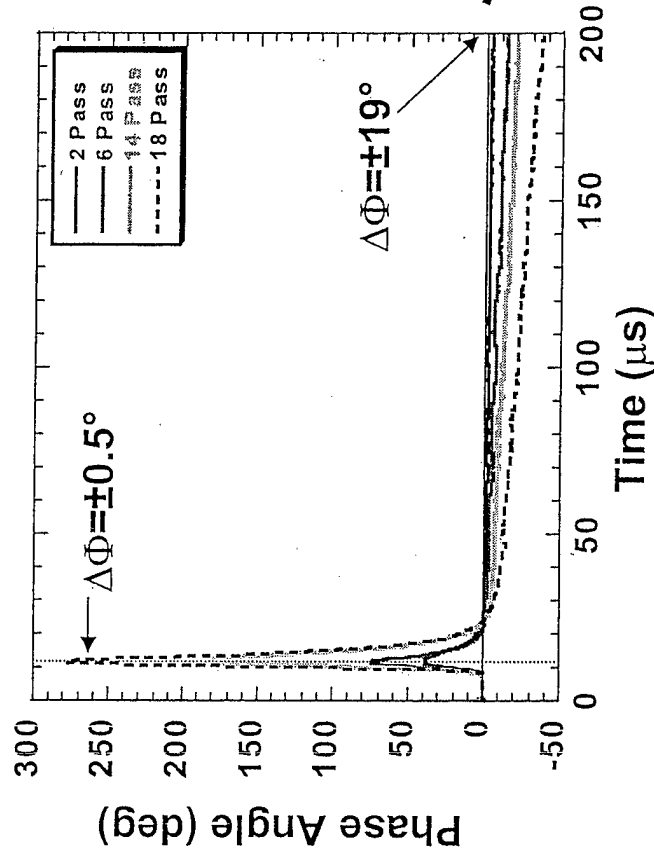
Change Analysis
Technique



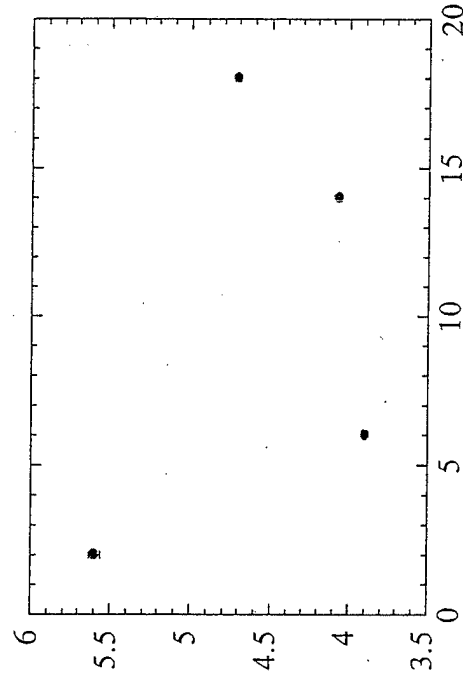
Experimental Results Show Increased Resolution



For single shots: Herriott Cell
enables detection of neutrals by
using 14-18 passes.

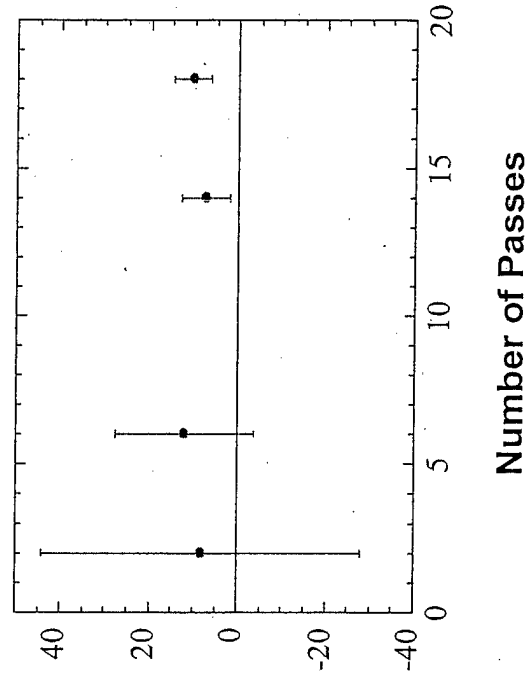


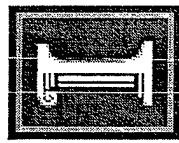
Electrons
at $12 \mu\text{s}$
(10^{15} cm^{-3})



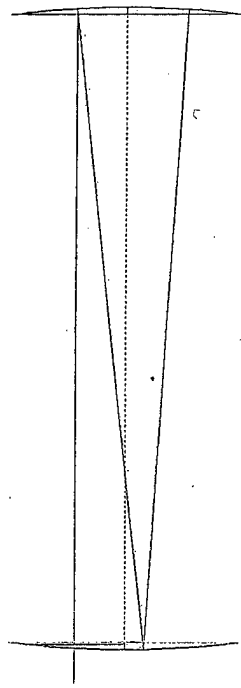
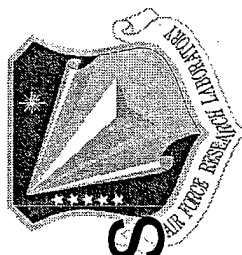
$$\Delta n = C \frac{\Delta\Phi}{N}$$

Neutrals
at $200 \mu\text{s}$
(10^{15} cm^{-3})

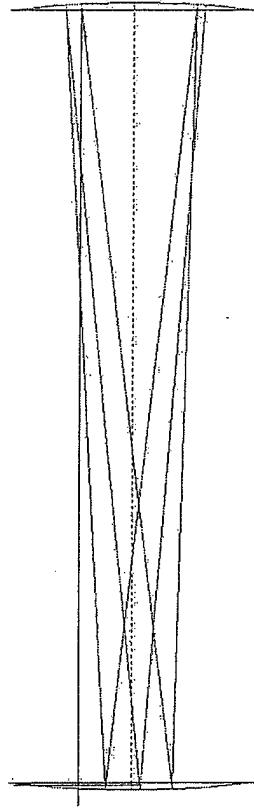




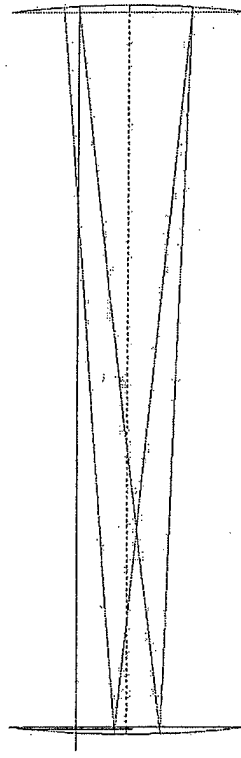
Retro-reflecting Configurations



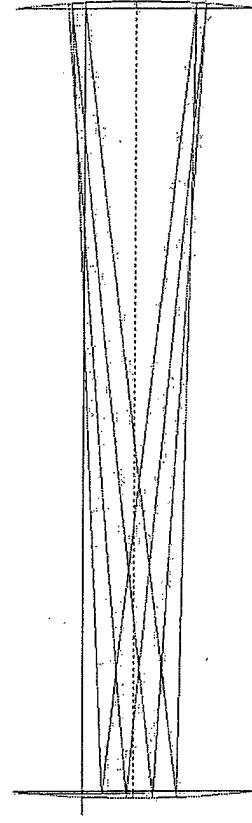
a.) 6 Pass, 140 mm Separation



c.) 14 Pass, 179 mm Separation

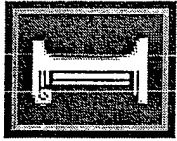


b.) 10 Pass, 168 mm Separation

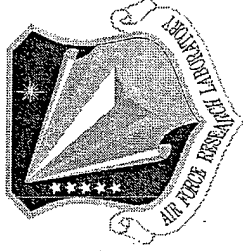


d.) 18 Pass, 184 mm Separation

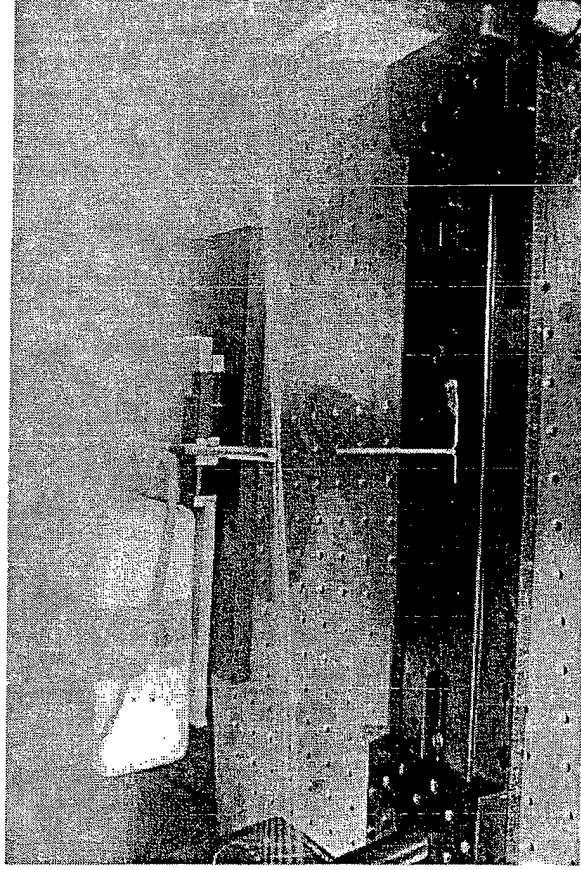
Various Retro-reflecting beam configurations using the Herriott Cell



Point Measurement Technique

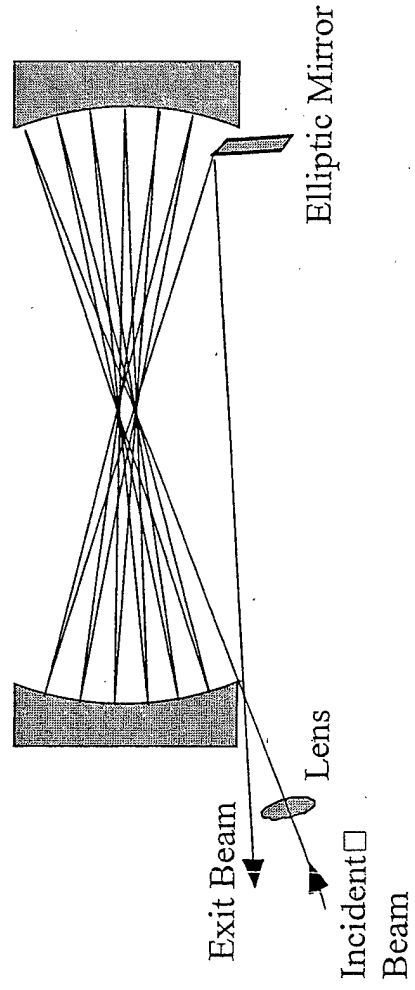


- Confine high number of beams to small area
- Increase signal-to-noise ratio

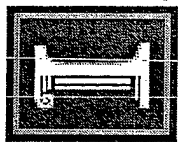


Herriott Cell Mirror

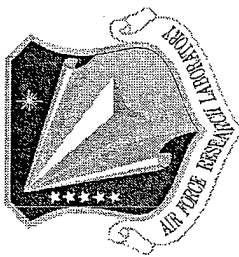
Herriott Cell Mirror



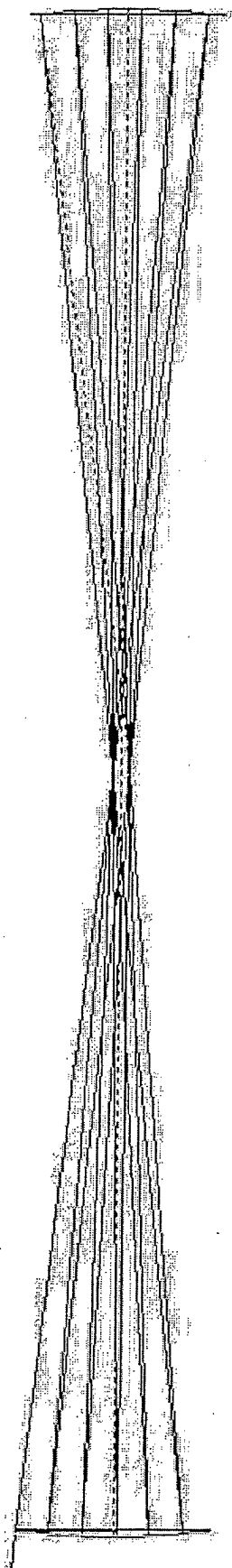
External optics required for point technique add some uncertainty



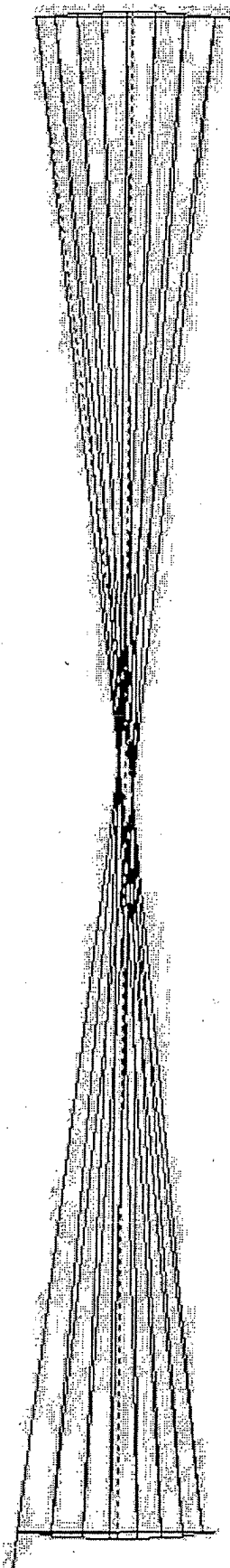
'Point' Configurations



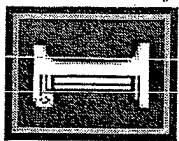
a. 9 passes, right mirror tilt angle 2.86°



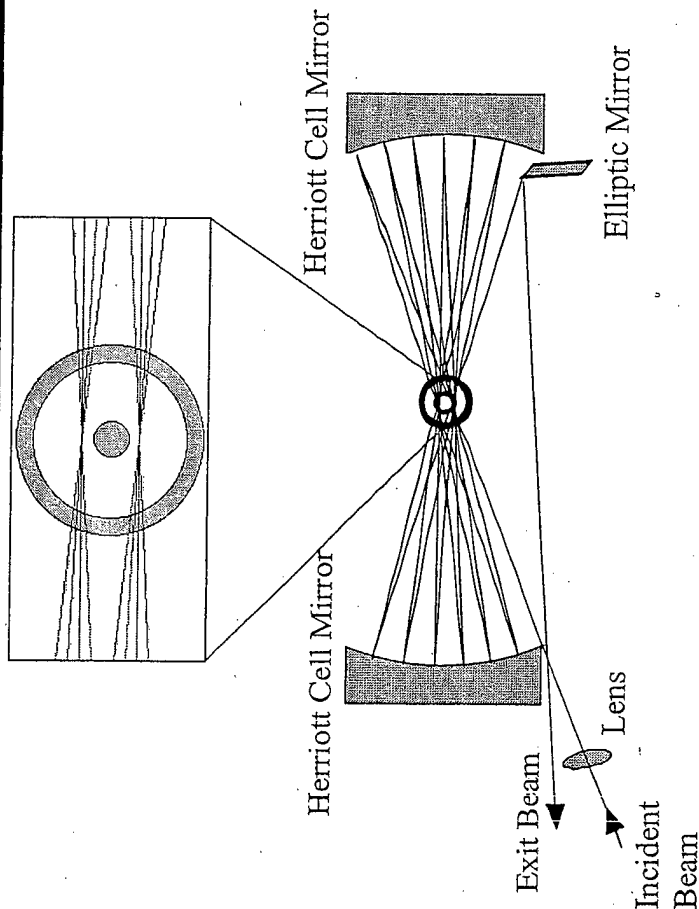
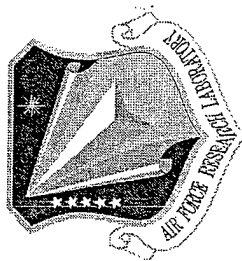
b. 13 passes, no mirror tilt



c. 16 passes, right mirror tilt angle -1.15°



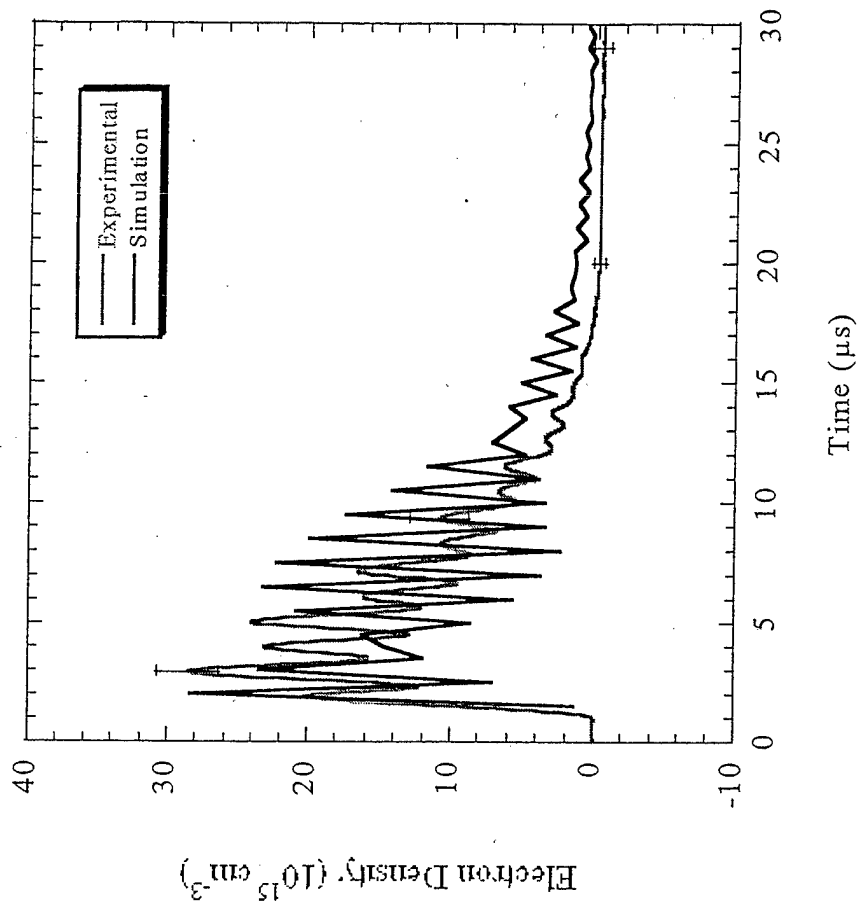
Herriott Cell Electron Density Measurement 1st Significant PPT Model Validation in 30 Years !

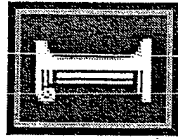


- Herriott Cell interferometer used to probe MicroPPT exhaust
- 'Point' measurement technique developed at AFRL allows measurements on small thruster geometries

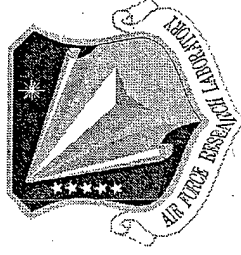
Herriott Cell electron density measurements show strong agreement with model predictions

Model simulation compared with
13 pass Herriott Cell measurement
1/4 in. DIA MicroPPT at 6.6 J





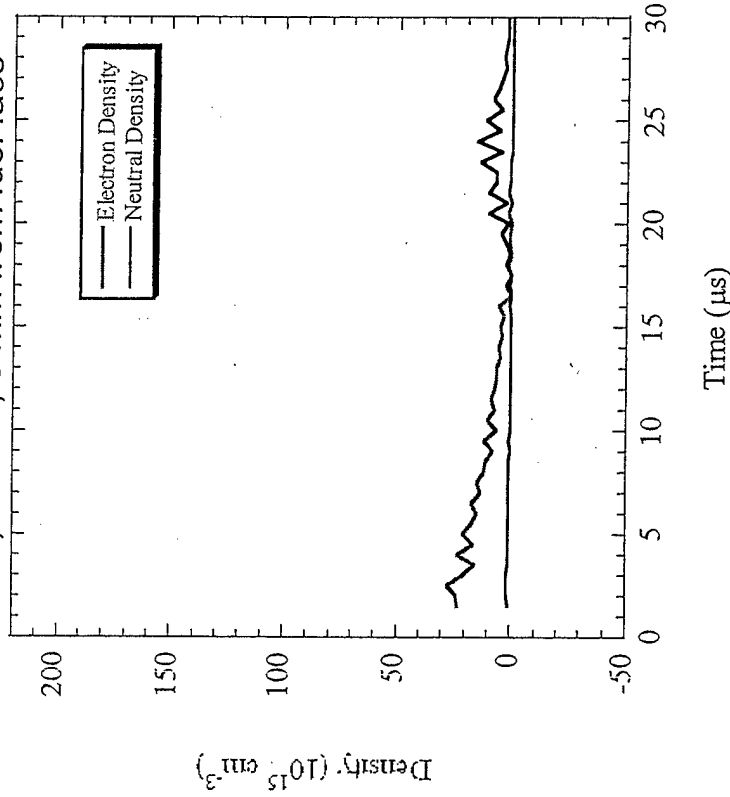
Neutral Density: Model and Experiment



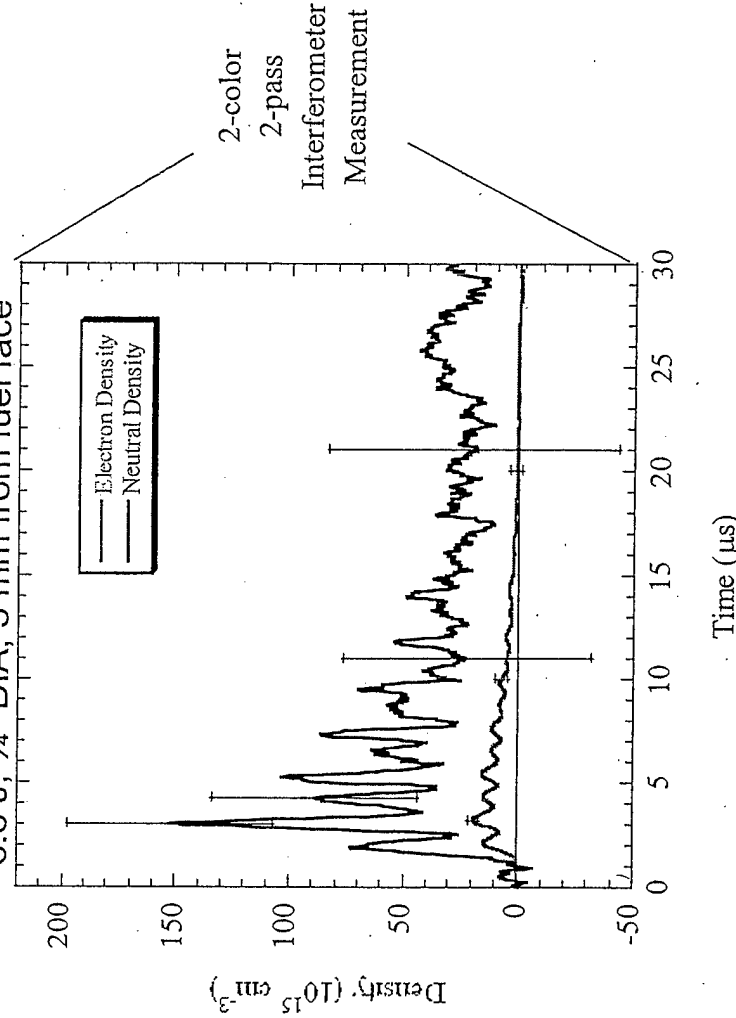
Plasma equilibrium assumption may be source of neutral density disagreement during the discharge between model and experiment

Neutral density determined by heat flux from plasma – surface temperature measurement can help correct the model

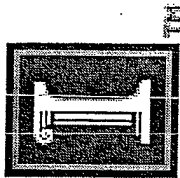
Simulated electron and neutral density
6.6 J, 1/4" DIA, 5 mm from fuel face



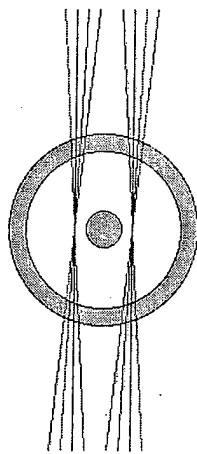
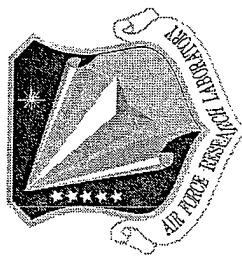
Measured electron and neutral density
6.6 J, 1/4" DIA, 5 mm from fuel face



New Diagnostic Development Needed to Check Model Sensitivity to Surface Temperature

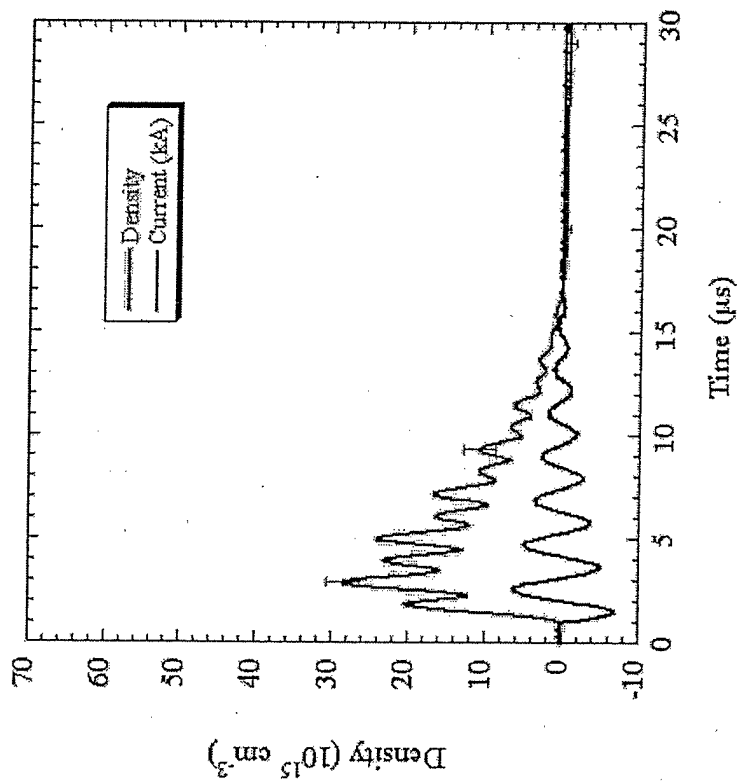
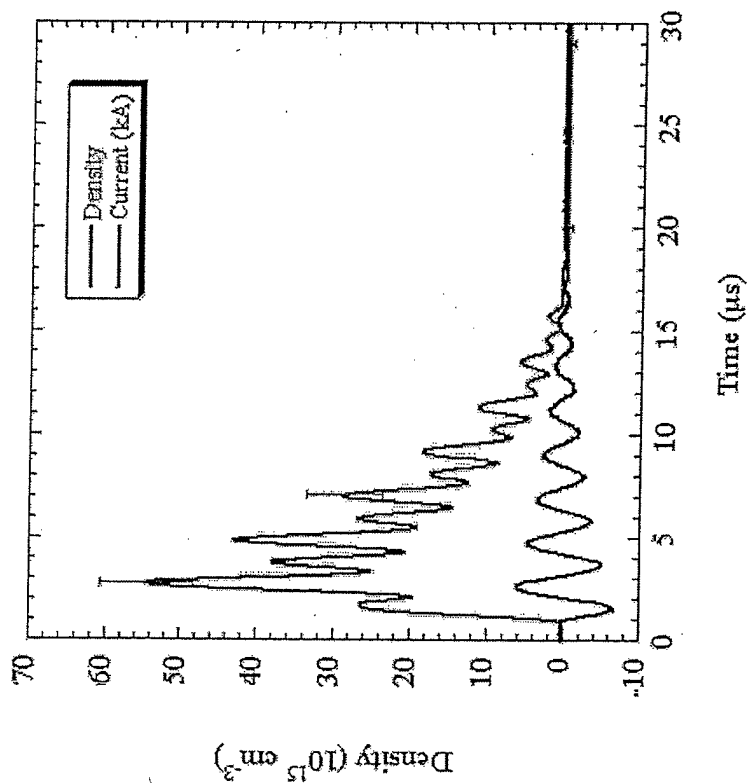


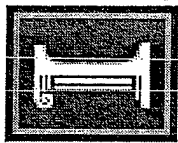
Electron Density Results



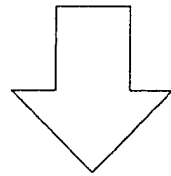
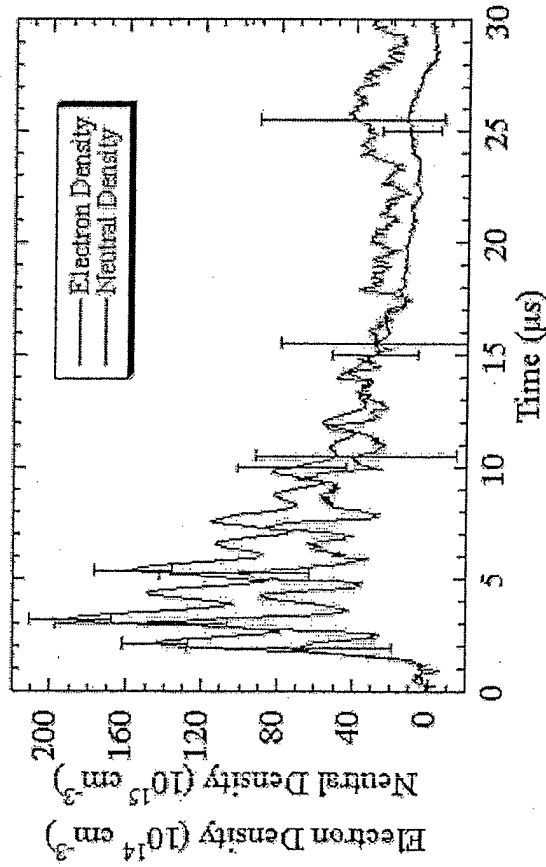
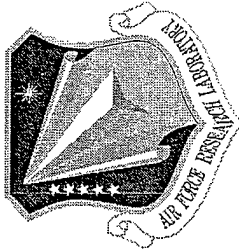
1 mm from fuel face
13 passes, 6.6 J

5 mm from fuel face
13 passes, 6.6 J



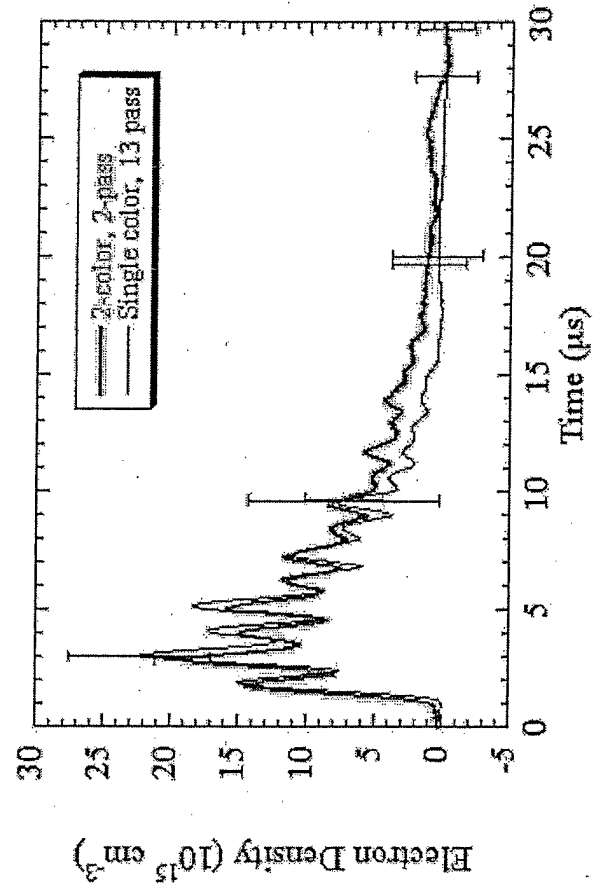


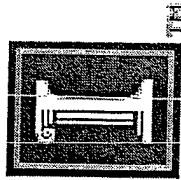
Two-Color Data



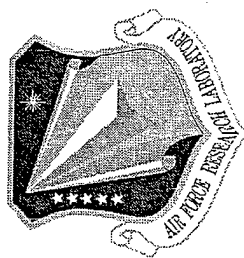
- Two color separation of electrons and neutrals
- Allows calculation of ionization fraction

Comparison of two-color data
with 13 passes Herriott Cell
show good agreement

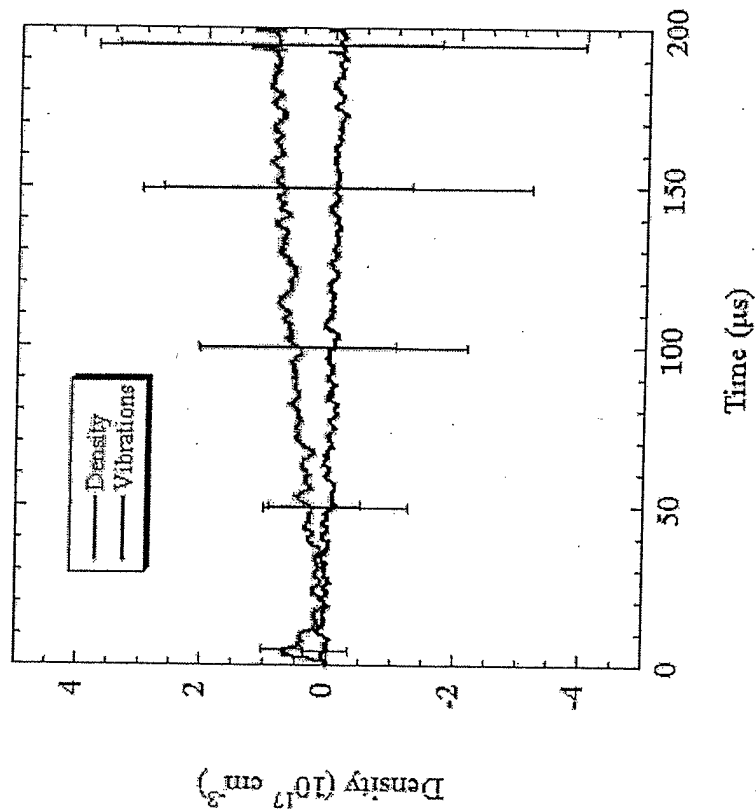




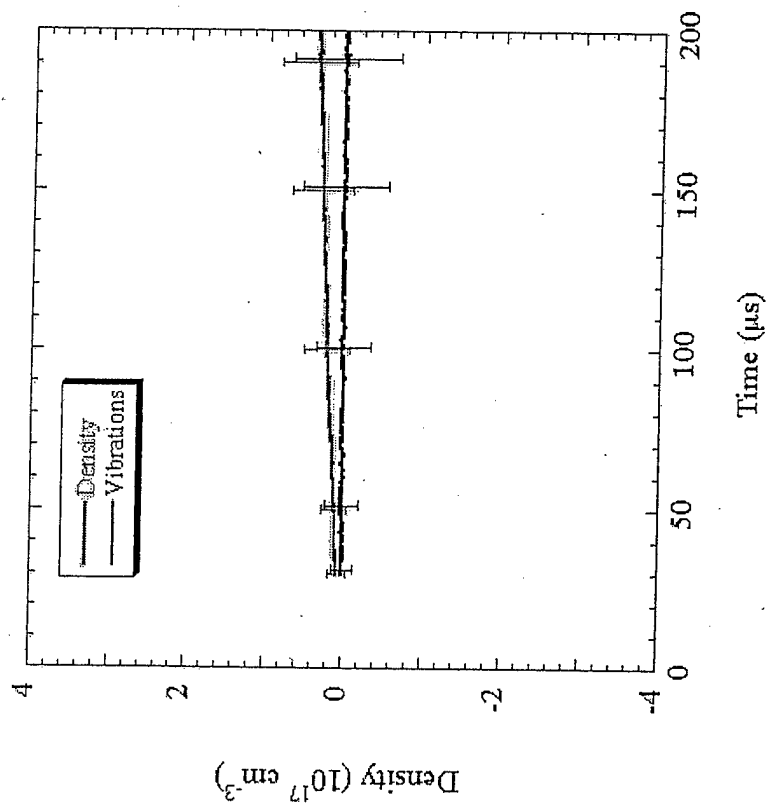
Neutral Density Uncertainty

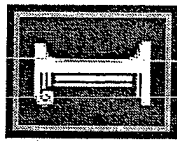


Two-color, two-pass
electrons and neutrals separated
but large uncertainty

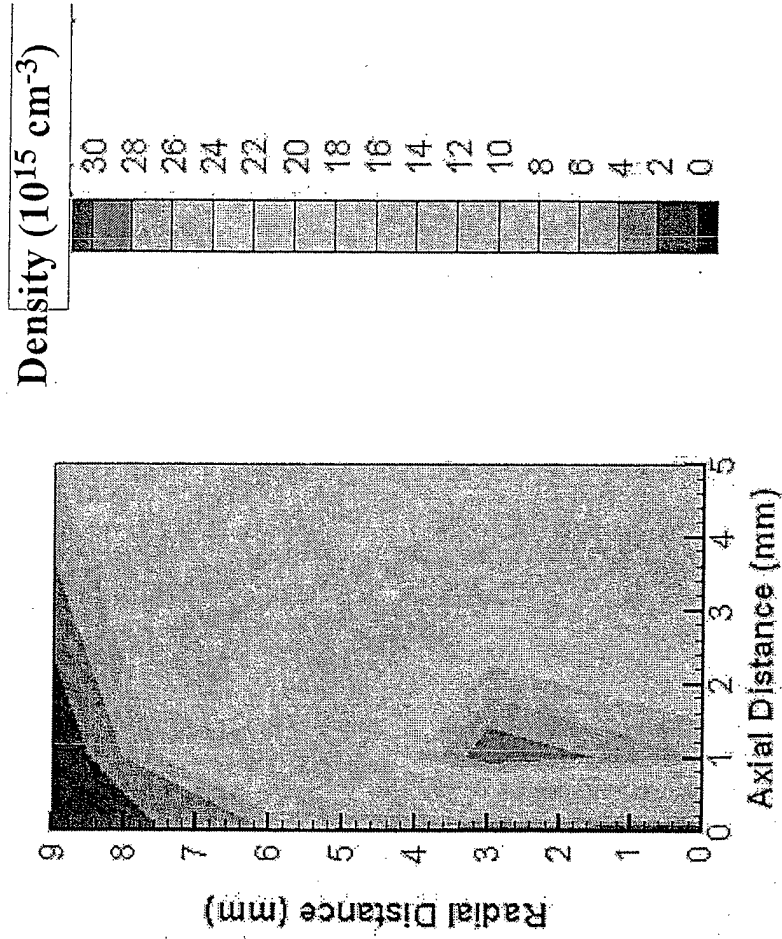
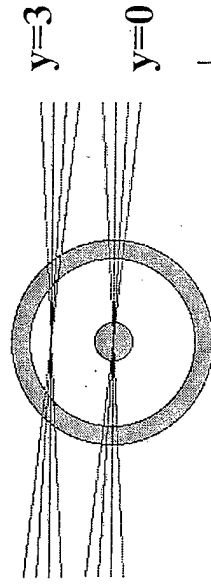
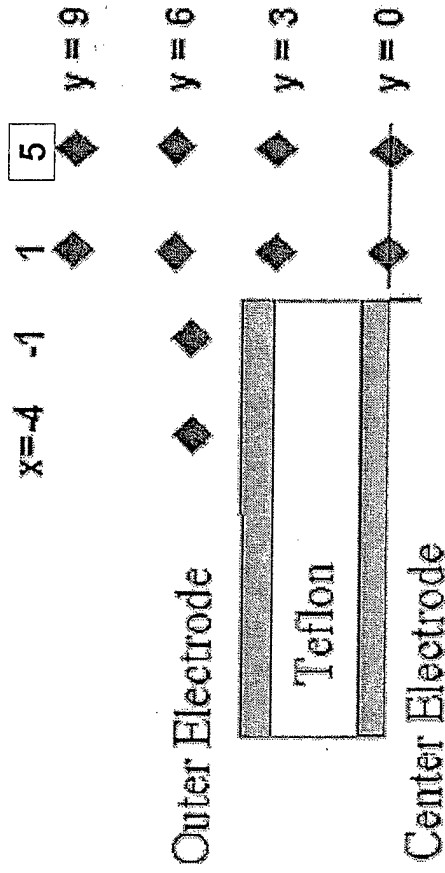
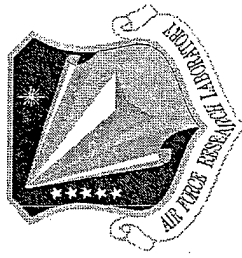


13 passes in Herriott Cell
show significant decrease
in uncertainty

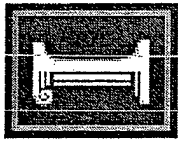




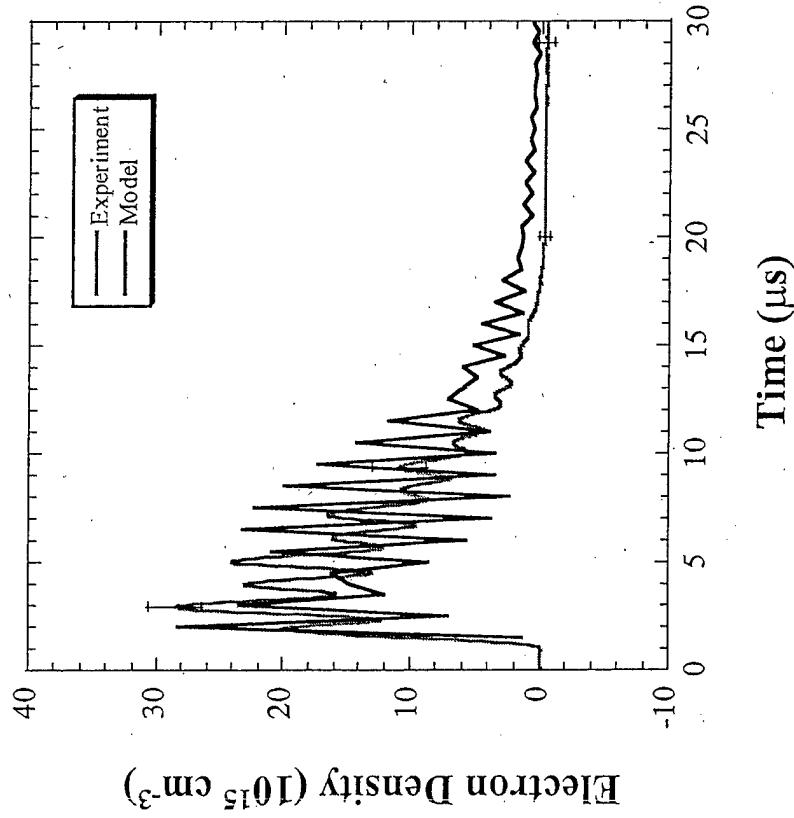
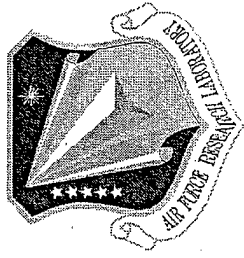
Peak Electron Density Results



- Peak electron density ($t=2\mu\text{s}$)
- Assume ($x=1, y=0$) has zero density, count in by focal points

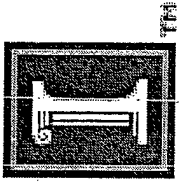


Direct Comparison

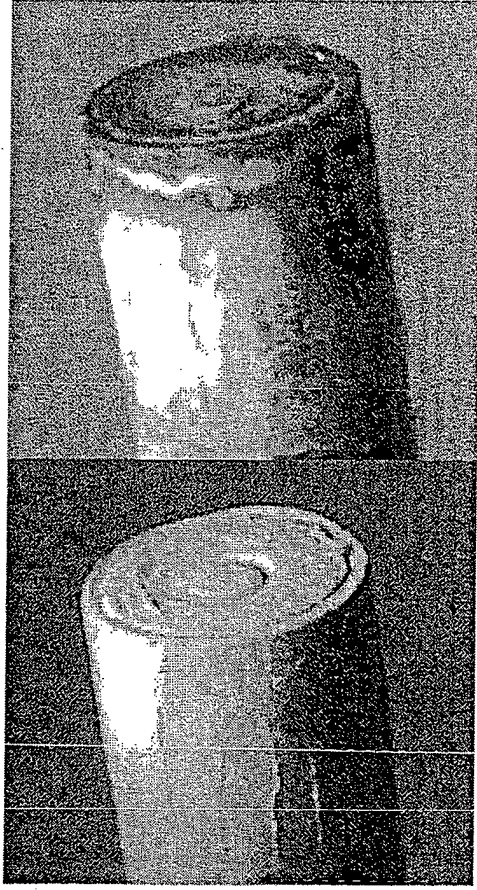
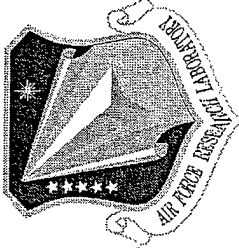


- Simulation uses measured current waveform as energy input
- 6.35 mm diameter, 6.6 J
- Measurement made 5 mm from fuel face
- Keidar and Boyd Model presented in IEPC 01-155

*delete or
replace
(releasability questioned)*



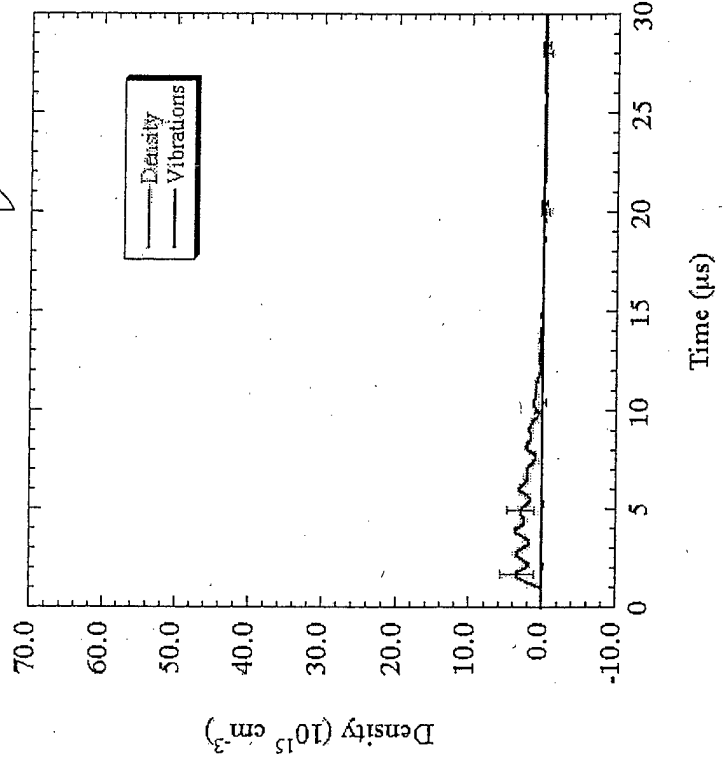
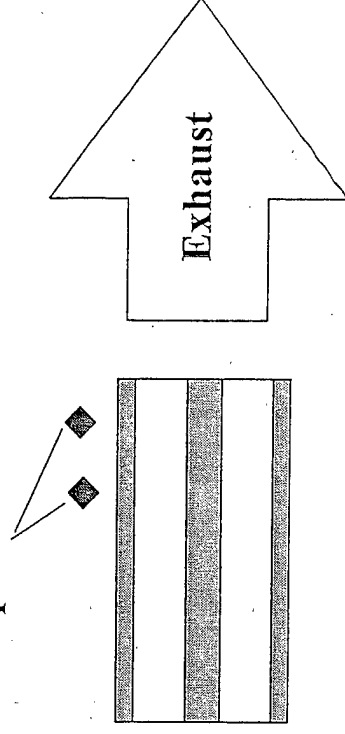
External Density Measurements

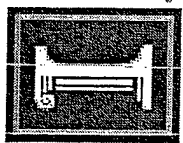


Barium Hydroxide coating on MicroPPT

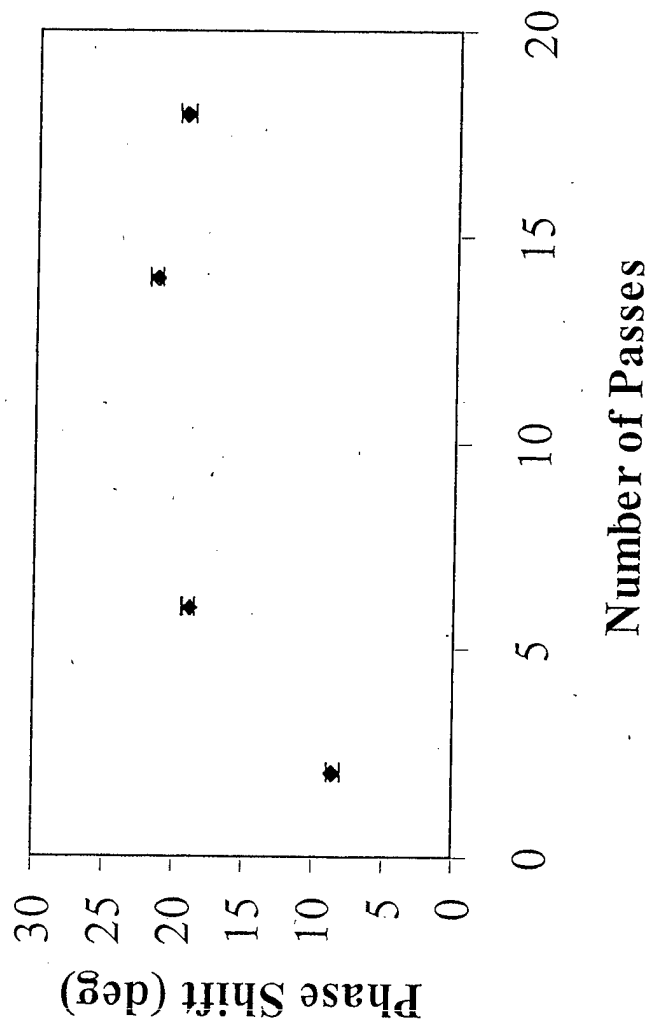
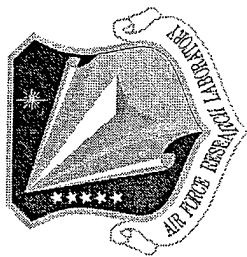
- Shows recession of 1-3 mm from thruster exit plane
- Corresponding external electron density measurements ($4 \pm 2 \times 10^{15} \text{ cm}^{-3}$)

HC focal points

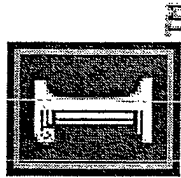




Vibrational Noise Effects



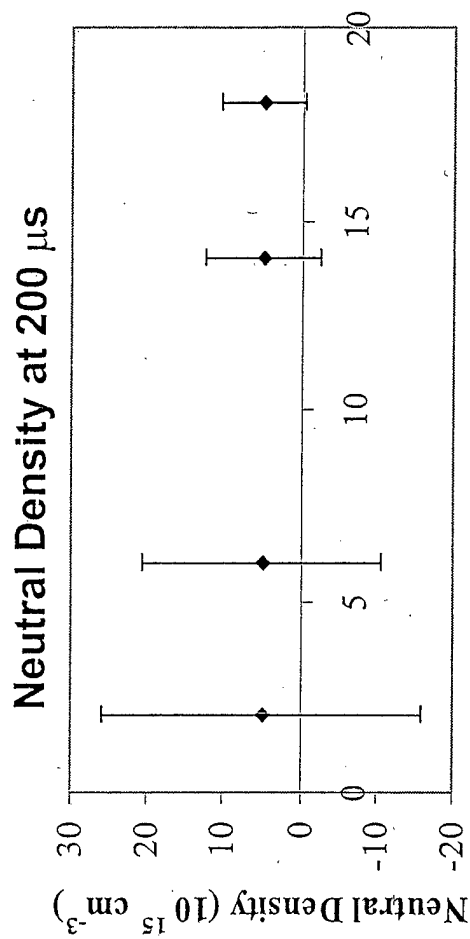
- No Plasma Present
- Data points average of 20 plasma firings
- Error bars due to 0.5° detector limitation



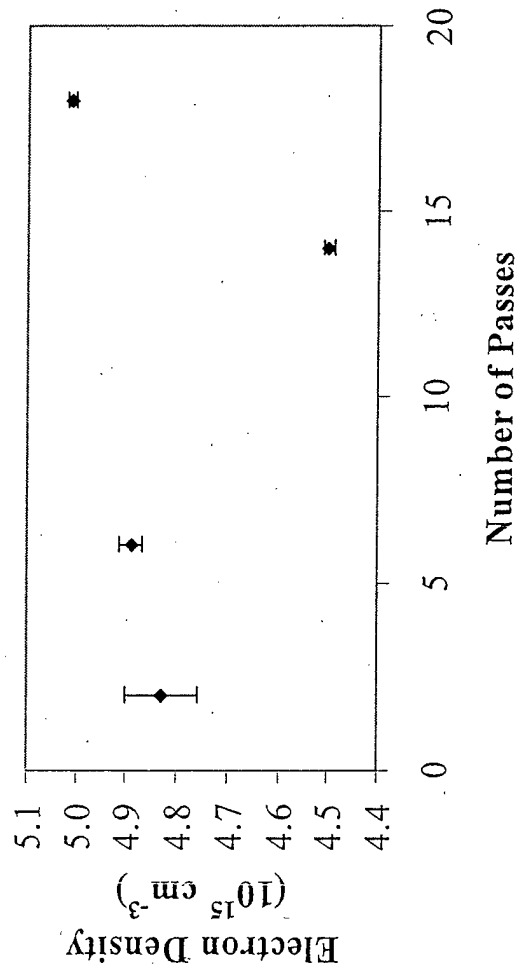
Effect of Multiple Reflections

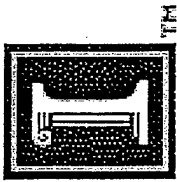


Data Taken at 2, 6, 14, and 18 reflections on UIUC PPT-4



Electron Density at 4 μs





Direct Comparison



- Simulation uses measured current waveform as energy input
- 6.35 mm diameter, 6.6 J
- Measurement made 5 mm from fuel face
- Keidar and Boyd Modeling effort (in submission to JPP)

